PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **118**: 1428–1442, 2006 October

The *Origins Billions Star Survey*: Galactic Explorer

K. J. JOHNSTON,[1] B. DORLAND,[1] R. GAUME,[1] G. HENNESSY,[1] R. OLLING,[1] N. ZACHARIAS,[1] B. BEHR,[1] M. EFROIMSKY,[1] A. HAJIAN,[1] H. HARRIS,[1] J. HILTON,[1] G. KAPLAN,[1] D. MONET,[1] J. MUNN,[1] J. PIER,[1] F. VRBA,[1] K. SEIDELMANN,[2] S. SEAGER,[3] S. PRAVDO,[4] K. COSTE,[4] R. DANNER,[5] C. GRILLMAIR,[6] J. STAUFFER,[6] A. BOSS,[3] D. CURRIE,[7] W. DANCHI,[8] A. GOULD,[9] S. KOPEIKIN,[10] S. MAJEWSKI,[2] V. MAKAROV,[11] R. MCMILLAN,[12] D. M. PETERSON,[13] E. SHAYA,[8] AND S. UNWIN[4]

Received 2006 June 20; accepted 2006 September 5; published 2006 October 18

ABSTRACT. The *Origins Billions Star Survey* is a mission concept addressing the astrophysics of extrasolar planets, Galactic structure, the Galactic halo and tidal streams, the Local Group and local supercluster of galaxies, dark matter, star formation, open clusters, the solar system, and the celestial reference frame by determining the position, parallax, and proper motion, as well as photometry, for billions of stars down to 23rd visual magnitude. It is capable of surveying the entire celestial sphere or dwelling on a star field by varying the cadence of observations. The mission's ability to measure objects fainter than 17th magnitude allows a large number of extragalactic compact objects to be observed, making the astrometric measurements absolute. The project mission accuracy is comparable to *Gaia* for a survey mission. Improved accuracy can be achieved by dwelling on a particular star field or by using the *Gaia* positions at 14th magnitude to improve the positions of objects at the 18th–23rd visual magnitudes.

1. INTRODUCTION

Space-based missions offer an order-of-magnitude improvement over ground-based observations in determining astrometric and photometric parameters for stars. The *Hipparcos* mission, which was conceived in the 1970s and flown in the early 1990s, determined positions, proper motions, and parallaxes at the milliarcsecond level, as well as *B* and *V* magnitudes at the 0.01 mag level, of 100,000 stars. It used a calibrated grid in the focal plane with a photon-counting detector to observe the modulated light of stars crossing the focal plane. A space-based survey mission using a large focal plane array consisting of CCDs observing a large field of view (FOV) of an order of $1° \times 1°$ offers the capability of surveying millions to billions of stars in a 5 year mission, and with precision astrometric and photometric measurements that are well beyond those of the *Hipparcos* mission. The *Full-Sky Astrometric Mapping Explorer* (*FAME*) mission, which was conceived in the late 1990s to measure 40 million stars, proposed the use of a focal plane consisting of twenty-four 2k × 4k CCDs to achieve an astrometric precision of 50 μas and a photometric precision of 100 mmag. It was a NASA Medium-class Explorer (MIDEX) mission funded at a level of $140 million in fiscal year 1998. This mission was canceled in 2001, due to cost and scheduling problems.

The *Origins Billions Star Survey* (*OBSS*) further develops the concept of a wide-FOV, large-focal-plane mission for determining the astrometric and photometric characteristics of billions of stars. The *OBSS* concept mission was studied under the NASA Astronomical Search for Origins Program. The Origins probe baseline was for a mission cost of $670 million in fiscal year 2004, to be launched in 2014. The resources for the *OBSS* concept mission were approximately equivalent to those of the ESA *Gaia* mission, scheduled for launch in 2011. The *OBSS* concept described here can not only accomplish most of the scientific goals of the *Gaia* mission, but will also go beyond

[1] US Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, DC 20392-5420.
[2] Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903.
[3] Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015.
[4] Jet Propulsion Laboratory, California Institute of Technology, 306-431, 4800 Oak Grove Drive, Pasadena, CA 91109.
[5] Northrop Grumman Aerospace Corporation, Mail Stop A01-26, Bethpage, NY 11714.
[6] *Spitzer* Science Center, 1200 East California Boulevard, Pasadena, CA 91125.
[7] Department of Physics and Astronomy, University of Maryland, College Park, MD 20742.
[8] NASA Goddard Space Flight Center, Exoplanets and Stellar Astrophysics Laboratory, Code 667, Greenbelt, MD 20771.
[9] Department of Astronomy, Ohio State University, 140 West 18th Avenue, Columbus, OH 43210.
[10] Department of Physics and Astronomy, University of Missouri at Columbia, 322 Physics Building, Columbia, MO 65211.
[11] Michelson Science Center, California Institute of Technology, 770 South Wilson Avenue, Pasadena, CA 91125.
[12] Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85712.
[13] Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
OCT 2006	**N/A**	**-**

4. TITLE AND SUBTITLE	
The Origin Billions Star Survey: Galactic Explorer	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Library U.S. Naval Observatory 3450 Massachusetts Avenue, N.W. Washington, DC 20392-5420**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

many of them. It can extend the astrometric and photometric capabilities to other stellar populations by allowing for a longer time of observations or by going to fainter magnitudes.

OBSS is a unique astrometric/photometric space-based mission that will map the Galaxy to unprecedented accuracies, determining the position, parallax, proper motion, luminosity, multiplicity, and photometric variability for over a billion stars in the Milky Way. The *OBSS* concept mission will provide observations of stars from 7th to 23rd visual magnitudes, with an astrometric precision of <10 μas and a photometric accuracy of 0.1 mmag at 15th visual magnitude. It will achieve Origins science goals by an astrophysical characterization of nearly all stars in the solar neighborhood, detecting their giant planets and low-mass companions.

2. SURVEY MISSIONS

Hipparcos and the planned *Gaia* mission both survey the sky by scanning with two apertures separated by approximately 60°–100° along the scan direction. Stars continuously pass through the telescope focal plane. CCDs in *Gaia* will be constantly read out in time-delay integration (TDI) mode. In this paper, another method, denoted as the step-stare mode, is presented. In this mode, the telescope is pointed at a star field. The CCDs are read out after the integration. Precise two-dimensional positions are obtained at once. The telescope is then pointed to a new field (or stepped) to give overlapping sky coverage. This mode has an advantage over scanning missions, which only obtain precise positions along the direction of the scan (one-dimensional). It is imperative to read out the CCDs and move the observatory/telescope as quickly as possible in order to obtain the efficiency of the step-stare mode.

Another proposed astrometric mission, the *Space Interferometry Mission PlanetQuest* (*SIM PlanetQuest*), is a pointed mission with an expected precision of 1 μas. Its primary mission objective is to detect the presence of planets around nearby stars. It is expected to survey about 1000 stars, with the capability of detecting a several-Earth-mass planet orbiting a star within 10 pc of the Sun. In other science areas, *SIM PlanetQuest* will have the capability of observing about 30,000 target stars, and in the context of surveying a large number of stars, it is not considered a survey mission because it will not perform a full-sky survey, complete to some limiting magnitude.

2.1. Scanning Survey Missions

The geometry of a typical scanning survey mission is shown in Figure 1. The satellite spins along an axis that precesses around a cone about 45° from the Earth-Sun line, with a period of 1 to 6 hr and a precession period of 20 to 70 days. There are two FOVs separated by 60°–110° around the spin direction. Seventy percent of the sky is completely scanned every 10–35 days (the Sun and anti-Sun regions are not observed, due to the precession half-angle), with 100% coverage every 6 months. In this way, an average of 100–1000 observations of each star are made, spread over 50–1000 epochs during a 5 year mission. Single-measurement accuracy is 1000 to <100 μas at 15th visual magnitude for a survey instrument with a collecting aperture of an order of 1 m, resulting in a single-epoch accuracy of 100–10 μas. The bandwidth of the system is 400 to 1000 nm. The photometric accuracy is estimated to be 0.1 mmag at 15th visual magnitude.

In scanning survey missions, two FOVs are used to establish a wide-angle reference for a star's position. This allows the referencing of star positions separated by about 90° to optimize the determination of absolute parallaxes. The precise astrometric measurements are made along the scan direction. A global solution based on the scans is then made for the entire sky.

2.2. The *Gaia* Mission

The scanning astrometric mission *Gaia* is scheduled for launch in 2011. Its optical configuration is a three-mirror anastigmat (TMA) design with an additional three folding mirrors. The system has a focal length of 35 m. Given an rms wave-front error of $\lambda/30$ at 600 nm, it is almost distortion-free and achromatic over the focal plane. The TMA has two apertures that illuminate a 1.45 m (in-scan) $\times$ 0.5 m beam-combining flat. These apertures are orthogonal to the spin axis and are separated by about 106°. Stars transit through aperture 2 about 100 minutes after passing aperture 1. Starlight is directed from each of the apertures via a series of secondary and tertiary mirrors and fold flats onto the focal plane. The illuminated plane is $0\overset{\circ}{.}7 \times 0\overset{\circ}{.}7$. The astrometric focal plane consists of about 63 astrometry CCDs. The pixel size is 10 μm along the scan direction, allowing 6 pixel samples across the stellar images. The CCDs will be read out in TDI mode, which will be synchronized to the satellite rotation rate. In addition to the astrometric instrument, blue (330–660 nm) and red (660–1000 nm) photometers will measure the colors of stars, and a high-resolution integral field spectrograph (named the Radial Velocity Spectrometer) will determine the space velocity of stars brighter than 17th magnitude that are located in the focal plane. The mission will be located at L2, reducing the effects of thermal loading from the Earth. With a rotation rate of 6 hr and a precession rate of 70 days along a cone angle of 50° in the antisolar direction, *Gaia* will obtain, on average, 90 observations of each of the billion stars to be observed over a 5 year mission. A more complete description of the *Gaia* mission is given in Perryman et al. (2001) and Turon et al. (2005), and also online.[14]

2.3. Step-Stare Survey Mission

It is possible to use a space-based telescope in a manner similar to that used for ground-based astrographs (Zacharias & Dorland 2006). The major problem with a single-aperture step-

[14] See http://www.rssd.esa.int/Gaia.

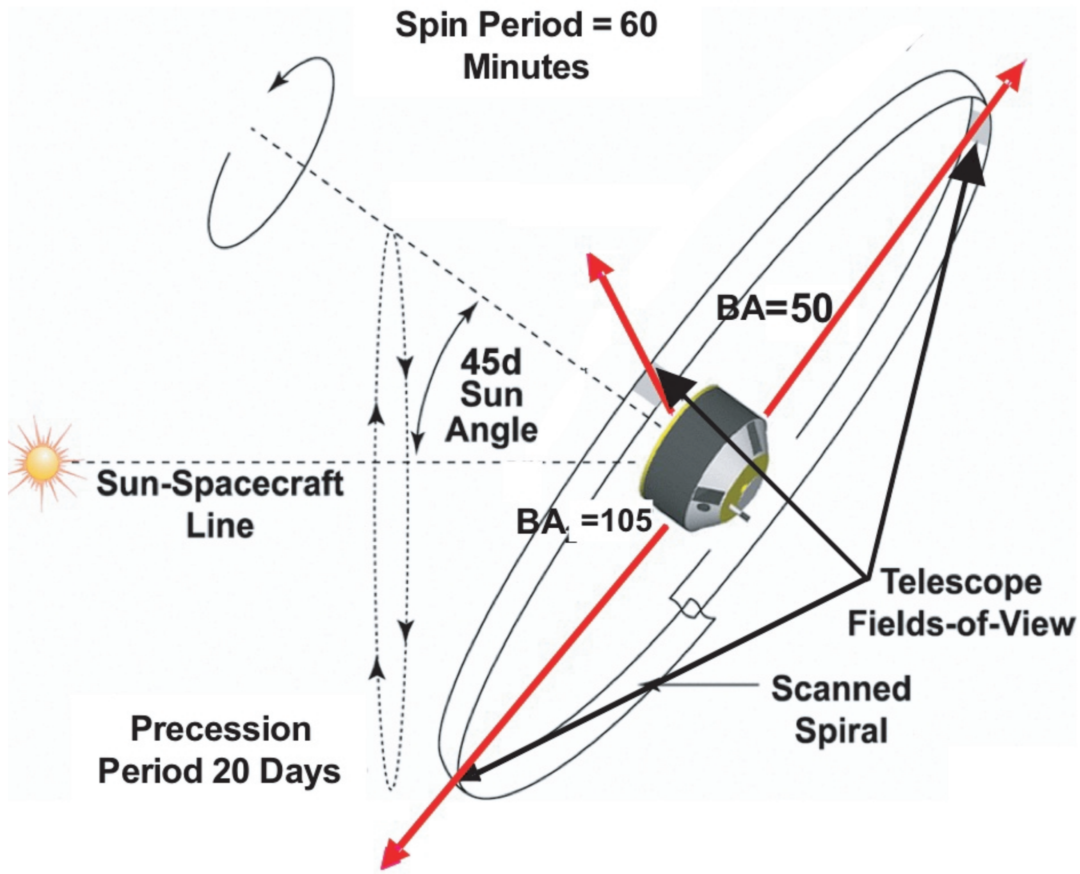

FIG. 1.—Typical *Hipparcos*, *FAME*, and *Gaia* geometry for a scanning mission.

stare mode is obtaining absolute parallaxes. The technique of block adjustment will be used with individual FOVs overlapping by as much as one-half of the FOV. With this method, the positions and proper motions are very "rigid" in an overlapping block (Zacharias 1992) using at least a hemisphere on the sky in a single reduction. Future global astrometric missions will be able to observe compact extragalactic sources, which are fixed on the sky. Given a telescope aperture that can observe to 20th visual magnitude, the parallaxes can be made absolute by using the extragalactic sources in the FOV as reference points.

2.4. *OBSS*

OBSS is a step-stare mission with a $1^\circ\!.1 \times 1^\circ\!.1$ FOV. The optical system is an off-axis, six-mirror anastigmat (SMA) design, with a primary aperture diameter of 1.5 m and a focal length of 50 m. In order to minimize chromatic effects over the bandwidth of astrometric operation (~550–900 nm), there are no refractive elements. To eliminate diffraction artifacts that could interfere with the astrometry, the design is off-axis, with no central obstruction or mirror supports in the optical path. The optical system has been designed to minimize distortion over the field (<0.001% at field edge) and meet a wave-front error (WFE) requirement of $<\lambda/15$ at 633 nm. The optical system is displayed in Figure 2, and details are summarized in Table 1.

The focal plane will consist of back-side–illuminated (5120 × 5120 pixel) CCDs with 10 μm square pixels. It is divided into four 5120 × 1280 pixel sections, each with a dedicated serial register, readout amplifier, and output port. This modular approach has been selected to increase yield, as CCDs will be cut and packaged on a section-by-section basis. The focal plane assembly will consist of 364 CCDs mounted in a circular pattern on a SiC table ~1.1 m in diameter, as shown in Figure 3. The total area covered by the 9 gigapixels is approximately 0.9 m^2.

The telescope will stare at a portion of the sky for 1.5 and 15 s exposures and then move $0^\circ\!.5$ and repeat this. A shutter is used to block light during readout of the CCDs. In this step-stare mode, both coordinates are measured in a single observation. Total observing time is $36^{s}\!.5$ per field. In this way, the entire sky can be covered in 30 days. Over a 5 year mission,

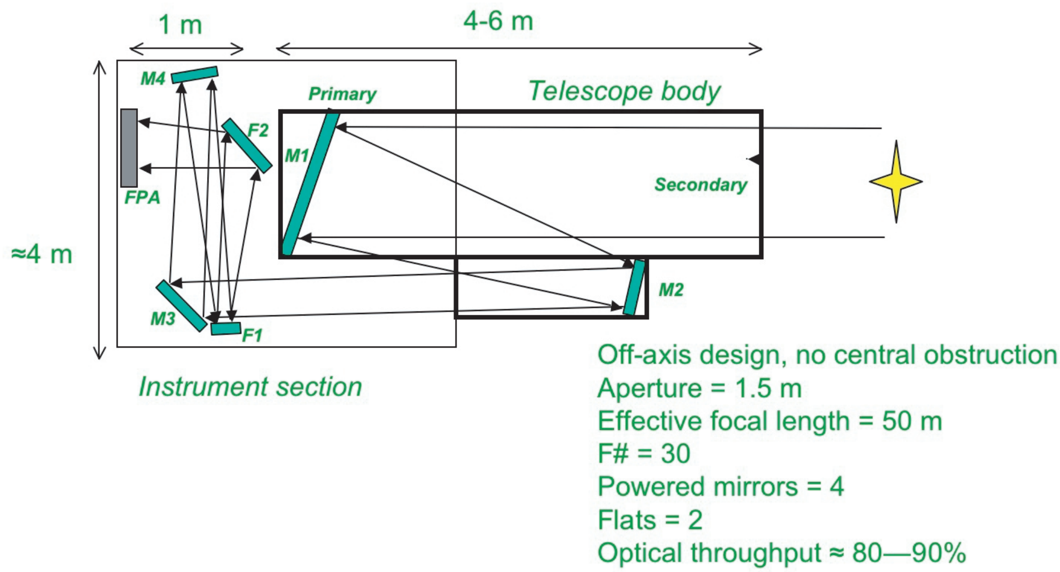

FIG. 2.—Optical system for *OBSS*. The optical system is an off-axis design. The focal plane size is an order of 1.1 m in diameter.

TABLE 1
OBSS PARAMETERS

Parameter	Value
Telescope	
Focal length (m)	50
Diameter of aperture (m)	1.5
Focal plane scale (mas μm^{-1})	4.13
Diffraction width at 0.6 μm (mas)	82.5
Focal Plane	
CCD size (pixels)	5120 × 5120
Pixel size (μm)	10
Number of CCDs	360
Wavelength range (nm)	400–900
Quantum efficiency	0.9
Readout rate (kpixels s^{-1})	655
Diameter of FOV (deg)	1.1
Sensitivity	
Magnitude range (visual magnitudes)	7–23
Astrometric accuracy, $m_v = 15$ (μas):	
Single measurement (15 s integration):	
A0	153
K2	129
M5	100
Estimated systematic error	5
Mission accuracy, 111 single measurements:	
A0	15
K2	13
M5	10
Mission	
Mission length (yr)	5
Orbit	L2

100–200 observations will be made of each star. Single-measurement precision in two coordinates will be 100, 129, and 153 μas at 15th visual magnitude for M5, K2, and A0 stars, respectively. Figure 4 shows the precision for single-position measurement accuracy for a K2 star as a function of magnitude. Mission accuracy in survey mode for the entire sky and for a 5 year mission lifetime, assuming a systematic error of 5 μas, will be 11, 13, and 15 μas at 15th visual magnitude for M5, K2, and A0 stars, respectively. Mission accuracy at 21st visual magnitude will be 95, 190, and 230 μas for M5, K2, and A0 stars, respectively.

The observing cadence can be tailored to the scientific objectives, making *OBSS* more flexible than *Gaia*. *OBSS* can stare at objects for long periods of time, thus extending its range to visual magnitudes of 22–23. By making 446, 15 s exposures in a targeted mode, accuracies of 7, 8, and 9 μas can be obtained at 15th visual magnitude for M5, K2, and A0 stars, respectively. At 21st visual magnitudes, these accuracies are 48, 97, and 114 μas, respectively.

The photometry needed for the astrometric calibration is accomplished with a low-resolution spectrometer. The light will be picked up in a FOV adjacent to the astrometric FOV. The reflected light will be dispersed through a beam-splitting filter tree into 16 different channels and sent through an optical path consisting of a fold-flat, collimator, grating, and refocusing mirror, onto a spectroscopy focal plane. This will give 16 distinct spectral channels between 320 and 1100 nm to determine the spectral energy distribution (SED) of stars.

Given the rapid cadence of the step-stare method, the spacecraft must be capable of slewing a half-degree and settling

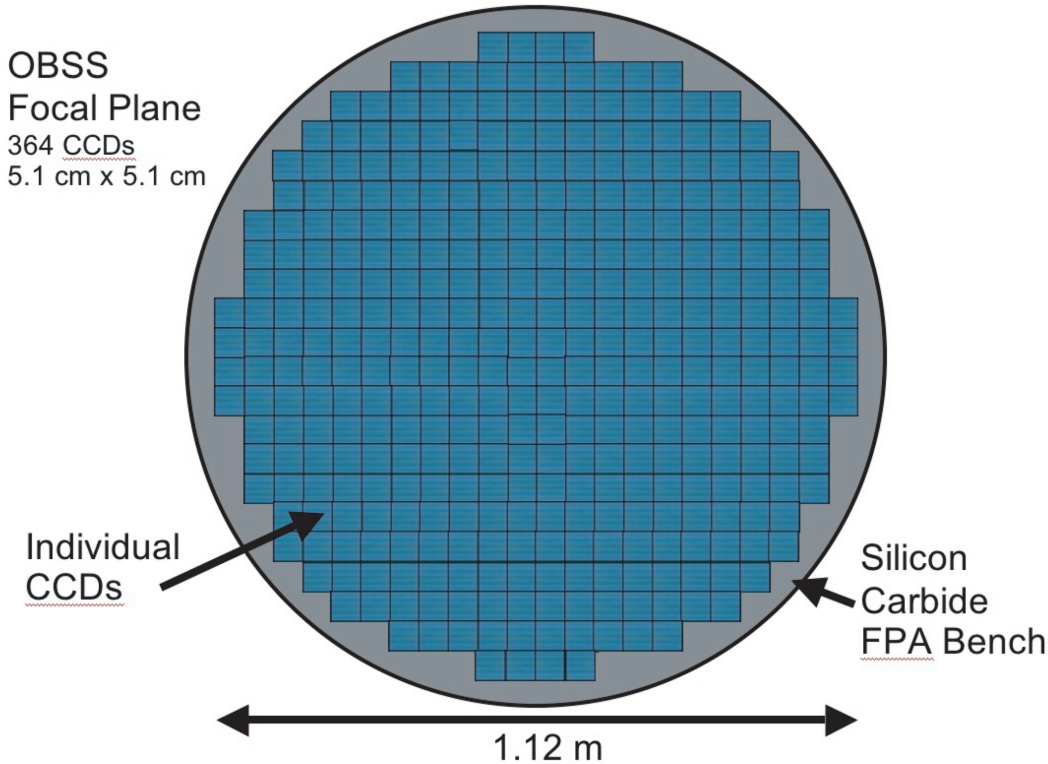

FIG. 3.—Focal plane array for *OBSS*. A FOV of 1°.1 in diameter is projected onto the focal plane. Both coordinates of the stars on the focal plane are determined in a single observation. The use of a circular focal plane allows the widest FOV to be observed for a given optical design.

quickly. In the above concept of operations, the spacecraft must accomplish this in 10 s. Control moment gyros (CMGs) capable of moving and settling in seconds will be used for the rapid slew and stop. CMGs are specifically designed to enable rapid application of moments by mechanically torquing the constant-speed wheel to a new angular position. The constant wheel speed allows significantly faster slew times and a greater degree of vibration isolation. Variable-speed reaction wheels (VSRWs) will accomplish fine-pointing control and motion damping. The pointing requirements are of an order of an arcsecond for observations with a jitter stability of less than 20 mas. In the scenario above, during the 10 s needed to read out the CCDs, the spacecraft moves one-half degree in 3 s using the CMGs, and accomplishes the fine pointing and motion control with the VSRW in 7 s.

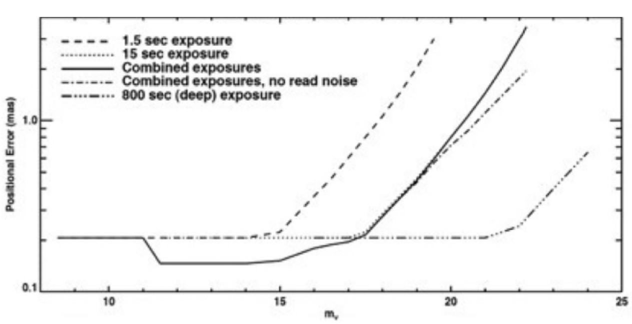

FIG. 4.—Single-measurement precision vs. magnitude for a K2 star. The dashed lines are for the 1.5 and 15 s data. The solid line gives the overall summed value for combining the data from the two integration times.

3. *OBSS* SCIENCE

The *OBSS* mission is very flexible in the choice of pointings and exposure lengths. Hence, the observing program and the science to be pursued can be adjusted at any time before or during the mission, based on the successes of other observing programs and the science that has been accomplished or that should be urgently pursued. In the following sections, possible observing programs and uses of the mission time are presented as examples of what could be accomplished with *OBSS*. Figure 5 shows the capabilities of the survey and pointed missions.

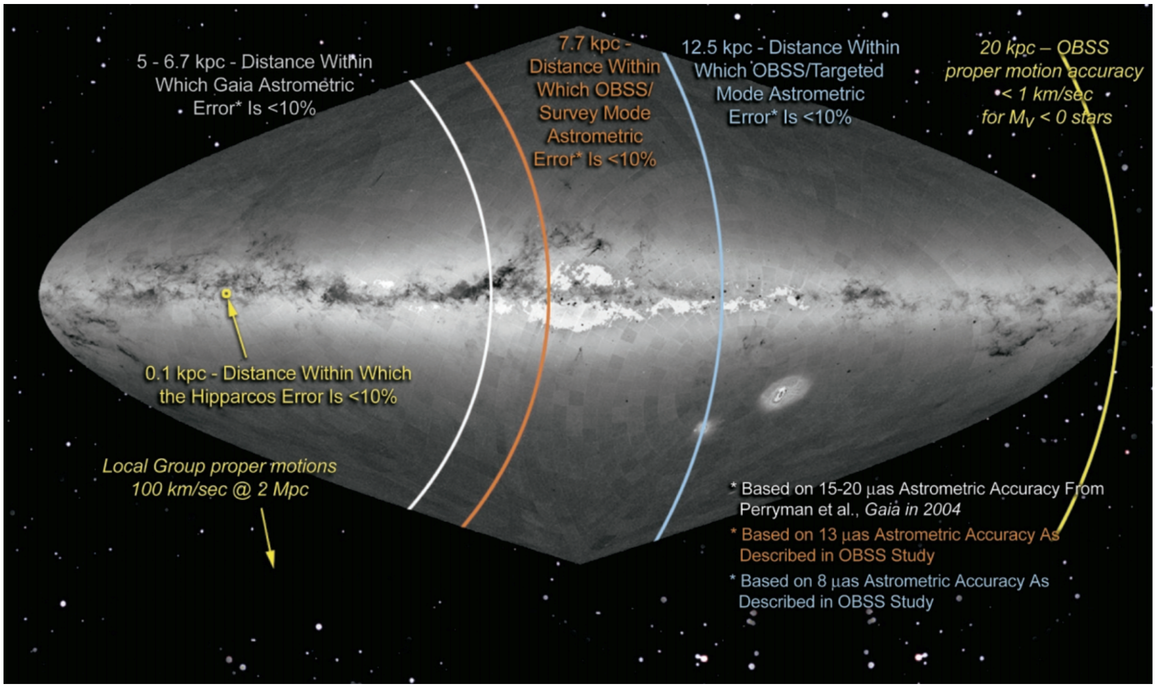

FIG. 5.—Capabilities of *OBSS* mission. In the pointed mode, 10% accuracy in distance is achieved for stars beyond the Galactic center. The survey modes of both *Gaia* and *OBSS* are roughly equal in area.

3.1. *Origins* Exploration Science

3.1.1. Planet Detection

The *OBSS* mission will search for planets and stellar companions by employing two techniques: (1) the astrometric detection of the reflex motion of the parent star, and (2) the photometric detection of planetary transits. While current ground-based radial velocity searches for extrasolar planets are limited to 8th visual magnitude and thousands of stars, the *OBSS* astrometric and photometric search will extend to beyond 18th visual magnitude and millions of stars. Using astrometric and photometric techniques, the *OBSS* in full-time survey mode should detect at least 28,000 and 1600 planets, respectively. These numbers could be improved by using an *OBSS* observing cadence that combines a full-sky survey with special targeted observing modes optimized for planet detection. *OBSS* will produce a census of the existence and physical characteristics of double stars, brown dwarfs, and giant planets around more than 2 billion stars.

3.1.2. Astrometric Detection

Astrometric detection of planets requires very accurate positional observations spread over the longest period possible so that solutions can be made for nonlinearities and periodicities in the proper motions of stars, along with determinations of parallax. For a 5 year *OBSS* survey-mode mission, a conservative astrometric detection threshold of 5 σ yields a detection of about 28,000 planets, 3000 of which would have determined orbits (where a determined orbit means that the period and semimajor axis are measured to 15 σ). This is illustrated in Figure 6. This level of astrometric accuracy is impossible to achieve from ground-based observatories. The orbital solutions have typical periods of 1–10 yr and lie within 200 pc of the Sun. After only 1.5 years of operation, *OBSS* will have discovered about 10 times more extrasolar giant planets (EGPs) than are known at this time. These numbers are for a full-time survey mode. Variation in observing modes can be used to optimize planetary studies. For example, combining a 25% survey mode with a 75% targeted field mode would allow dense star fields to be selected for more observations in order to both improve the astrometric accuracy of individual epochs and increase the number of observation epochs for concentrated planet searches. Because of the flexibility of *OBSS*, up to 3.75 years spread out over the mission could be dedicated to planet detection, allowing, for example, as many as 6000 more planets to be detected around special subsets of stars. A 5 year time span is necessary to detect a large number of planets with long periods.

The number of EGPs that can be detected astrometrically by *OBSS* is estimated from models for the distribution of stars (brighter than 18th visual magnitude) in the solar neighborhood and the probability density function (pdf) that describes the fraction of stars with EGP companions as a function of EGP mass and orbital period (Tabachnik & Tremaine 2002). In our

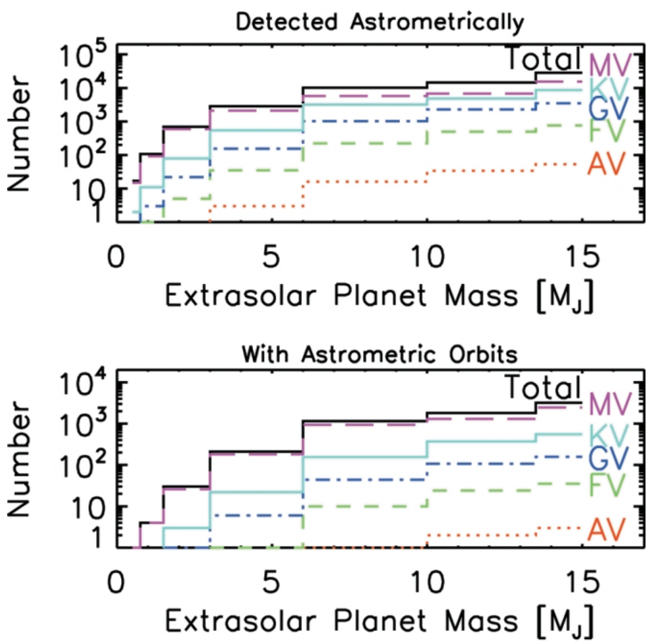

FIG. 6.—Predicted number of detections (*top*) and determined astrometric orbits (*bottom*) as a function of planetary mass and spectral type of the primary for *OBSS* from a 5 year survey mission. Similar numbers can be achieved with shorter total observing time by concentrating on denser fields in the Galactic plane.

model, the stellar density distribution decreases exponentially away from the plane but is constant in the plane of the Milky Way. To estimate the brown dwarf detections, we use an extrapolation of the EGP pdf by Tabachnik & Tremaine (2002) to masses larger than $10M_J$.

As a rule of thumb, the orbits of companions can be determined to accuracies similar to those of the parallax if the orbital period is shorter than twice the mission duration (Soederhjelm 1999). Detecting the presence of a companion requires the determination of the acceleration (curvature) term of the proper motion (e.g., Eisner & Kulkarni 2001; Kaplan & Makarov 2003).

3.1.3. Photometric Detection

The photometric detection of planets requires very accurate, repeated photometric observations over a period of time in order to detect a planetary transit lasting a couple hours in front of a star. Since an astrometric survey with overlapping exposures does not follow this pattern, the photometric detections could be best accomplished by periods of special observations, which could be spaced throughout the mission as part of a combined all-sky, targeted field observing cadence.

3.1.4. Applications of Detection Information

With the capability of monitoring bright stars (as bright as 7 mag) with short exposures, the *OBSS* can screen most nearby potential *SIM PlanetQuest* and *Terrestrial Planet Finder* (*TPF*) targets for giant planets in long-period orbits. Detection of cold Jupiters can directly benefit *TPF* by (1) identifying systems that are candidates for terrestrial planets in the habitable zones, and (2) defining the orbital plane orientations for these *TPF* candidate systems, thus reducing *TPF* search times. The near-simultaneity, as originally envisioned in 2004, of the *OBSS* 2014 and *Terrestrial Planet Finder-Coronagraph* (*TPF-C*) 2014 missions would be particularly useful, since *OBSS* measures the semimajor axis of the photocenter, while *TPF-C* determines the actual position difference between the star and the EGP. In principle, combining a single *TPF-C* position measurement with the *OBSS* orbit of the photocenter allows for an accurate determination of both the stellar and planetary mass. If there are multiple giant planets present in a system, *TPF-C*'s positional information for these components will be particularly useful in deriving the masses of the EGPs.

OBSS can provide a target list for further study of up to 10,000 additional transiting EGP candidates that are brighter than about a Johnson-Cousins *R* (Bessell 2005) magnitude of 13.5 and are closer than 600 pc. *OBSS* will provide astrophysical parameters for these stars, including stellar age. The *OBSS* transit targets will be significantly closer and brighter than the *Kepler* detections, allowing much easier follow-up for confirmation of the period and spectral characterization of the primary, and even planet characterizations; e.g., primary atmospheric transmission spectra and secondary-eclipse thermal emission spectra with the *James Webb Space Telescope* (*JWST*).

3.1.5. Census of Planetary Systems around Stars of All Ages

OBSS will have astrometric detections of 28,000 EGPs out to 200 pc; 3000 of these planets will have orbital solutions. Masses can be determined for planets with orbits, given the parent star mass (the error depends on the parent star mass), and they can be estimated for stars without orbital solutions. *OBSS* will definitively provide planet mass distributions down to a few Jupiter masses at periods from 1 to 10 yr around mid-F through M stars.

3.1.6. Binaries, Brown Dwarfs, Stellar Companions

Astrometric detection of long-period binaries is realized via differences between short-term and long-term proper motions, or via accelerating tangential motions (Kaplan & Makarov 2003). Stellar-mass, short-period binary black holes are fairly common in the Galaxy. Dynamical masses have already been estimated for 17 black hole binaries (Orosz et al. 2002). *OBSS* will be ideally suited for detection of astrometric black holes in the vicinity of the Sun. Accelerations as small as 100 μas yr^{-2} will be reliably determined for stars brighter than 16 mag. More importantly, the major uncertainty about *Hipparcos*-selected black hole candidates, whose distance (~1 kpc) cannot be inferred from the *Hipparcos* parallaxes, will be removed.

OBSS will determine the frequency and orbits of brown dwarfs in the $13M_J$–$80M_J$ range with $P_{orb} < 10$ yr around A through M stars.

The paucity of brown dwarfs with short-period orbits around solar-type stars has been firmly established by spectroscopy. Whether this "brown dwarf desert" extends into the domain of orbital periods larger than 4 yr is not known (Liu et al. 2002). The number of brown dwarf companions around M dwarfs is not at all certain. Ground-based astrometry indicates that a high percentage (>20%) of low-mass stars have companions with late M, L, or T spectral types (e.g., Pravdo et al. 2005). Figure 7 shows the domains of detectability for brown dwarfs via accelerated proper motions of the primary stars and via full orbital fits. Long-period brown dwarf companions will be discovered around stars out to 500 pc, and short-period ones to 1000 pc. The empirical distribution of orbital periods of binary main-sequence stars is peaked at 173 yr (Duquennoy & Mayor 1991). *OBSS* is expected to detect roughly half of all brown dwarf companions in the Hyades, for example. It is important to compare the rates of binary and free-floating brown dwarfs in open clusters. The recent finding that low-mass companions are rarely found in long-period binaries with stars earlier than type F (Makarov & Kaplan 2005) will be verified.

3.1.7. Statistics for M Star Planet Formation

Knowledge of the masses of planets in systems containing low-mass stars is critical to our understanding of planet formation (Laughlin et al. 2004; Boss 2006). Microlensing searches probe M stars but often miss orbiting planets, due to lens parameters and planet positions. Radial velocity surveys probe M stars, but due to their faintness, the surveys are limited to a few hundred stars. It is anticipated that *OBSS* will detect planets around several thousand M stars; 300,000 to 1 million M stars will be surveyed. No other mission is capable of studying such a large number of M stars.

3.1.8. Physical Properties of Extrasolar Giant Planets

Radius and mass are crucial for determining density and thus for gaining an understanding of the bulk composition of giant planets. They are the main, essential constraints to planet evolution. A large number of transiting planets are necessary in order to understand the range of possibilities. Current ground-based programs are already developing efficient methods to detect planets from among a large number of transit planet candidates. *OBSS* can provide a catalog of up to 10,000 short-period giant planet transit candidates that would be suitable for ground-based radial velocity follow-up measurements to determine the companion mass and confirm the planetary nature. *OBSS* will provide 40 times more candidates than are expected from ground-based surveys alone.

The transiting planets, particularly the brighter ones, can be characterized by atmospheric detection in the combined light of the planet-star system. The *JWST* will be capable of obtaining both transmission spectra measurements during a transit and thermal emission spectra measurements from a secondary eclipse (Mandushev et al. 2005; Deming et al. 2005). Having a large sample of short-period planets is key for planet characterization and an understanding of the physical properties of giant planets and even their formation and migration histories.

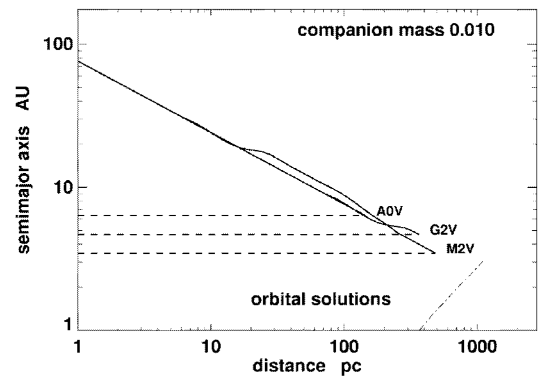

FIG. 7.—Domain of detectable binary brown dwarf companions. The region above the dashed line to the solid line is the area where brown dwarf companions are detected via the accelerated proper motions of their primary stars in the dedicated survey mode. Those found by full orbital fits are to the left of the dash-dotted line.

OBSS data will enable the accurate determination of the critical physical parameter of planetary mass. Combining astrometric measurements of the photocenter of a star and planet with radial velocity measurements from ground-based observatories, or with transit observations, will expand the sample of observed extrasolar planets significantly beyond the target lists of the *SIM PlanetQuest* and *TPF* missions. Like *TPF-C*, *OBSS* is most sensitive to EGPs several AU from the parent star. The combination of *OBSS* astrometric orbits of the photocenter and direct imaging obtained with *TPF-C* will yield very accurate orbital elements, in addition to the mass of the star and the EGP. The potential scientific payoff is significant; for example, the combination of observations and theory may help determine whether the central cores of giant planets are made up of heavy "rocky" elements or lighter gases.

Combining astrometric observations of the projected orbit in the plane of the sky with ground-based radial velocity measurements will enable complete orbital determinations of these planets. *OBSS* will be able to probe hundreds of stars for the presence of massive, long-period planetary companions.

The inadequacy of planet formation models, when confronted with the first actual observations of extrasolar planets, clearly indicates that knowledge of the complicated physical phenomena governing the formation and evolution of planetary systems is still partial. The observational selection effect on current discoveries limits the statistics and range of possible planetary systems. The interplay between additional theoretical work and more observational data is instrumental for continued improvement in the theory of how planets form and evolve and where Earth-like planets could eventually be found.

3.1.9. Planets and Debris Disks

OBSS will be able to detect massive giant planets in wide orbits around a number of stars, thus calibrating the debris disk SED and the presence of giant planets. Giant planets shape debris disks, causing structure and gaps. This disk structure is evident even in the disk SEDs; i.e., the wavelength-dependent infrared emission from the spatially unresolved disk. *Spitzer* will be observing a large number of stars of all ages. There are legacy GTO and GO programs to look for SEDs of debris disks. Interesting *Spitzer* targets can be scheduled for follow-up observations using *OBSS*.

3.2. The Milky Way, Galactic Structure, Local Group, Local Supercluster, Dark Matter, and Cosmology

3.2.1. The Local Velocity Field of the Galaxy

Several recent developments indicate that the understanding of stellar motions in the solar neighborhood needs refinement. The "standard" models describing the local velocity field (the Oort model, the Ogorodnikov-Milne model; Du Mont 1977) are all low-order expansions of a general velocity field. Observational data from the *Hipparcos* mission showed very significant evidence for stellar streaming motions that were wholly inconsistent with the standard model (e.g., Dehnen 1998, 1999; Olling & Dehenen 2003; Vityazev & Shuksto 2004; Famaey et al. 2005; and many others). Furthermore, because the mass of the Milky Way has changed dramatically between Galactic infancy and the present time, it is expected that the kinematics of the Milky Way will depend on the age of stellar populations. The simplest version of such temporal dependence is the already known age-velocity relation, which states that the velocity dispersion of stellar populations increases with their age (i.e., with time). The observed dependence of the Oort "constants" on asymmetric drift (Olling & Dehenen 2003), combined with the well-known relations between age, velocity dispersion, and asymmetric drift, imply that the Oort constants vary with time, and it is expected that other age dependencies will be uncovered by employing *OBSS* data.

OBSS data will uncover a whole range of "new" phenomena, in addition to those hinted at already by present studies, such as kinematical signatures of (1) the stellar bar, (2) interactions with the spiral arm structure (density wave), (3) the Galactic warp, (4) nearby dwarf galaxies (Sagittarius dwarf, Magellanic Clouds), (5) cannibalized dwarf galaxies, and (6) massive dark objects. These hypotheses can be tested and verified with more accurate astrometric data. For example, *OBSS* will help to resolve the problem of the structured velocity field in two ways. The horizon of the "local" field will be pushed dramatically from ∼200 pc with *Hipparcos* to 5–7 kpc for the abundant red clump giants ($M_V = 0$) if no age information is required, and to 1–3 kpc for late F and early G main-sequence (MS) stars where the *OBSS* parallaxes will still be accurate enough to untangle the large-scale rotation from the small-scale effects. Thus, local perturbations and their physical causes will be determined in about 20% of the Galaxy. This will open a new era in Galactic dynamics. Perhaps more importantly, *OBSS* will detect and perform astrometry on practically all stars within 200 pc to $M_V = 14.5$.

3.2.2. The Large-Scale Velocity Field of the Milky Way

The targets that are probably best suited for rotation curve studies are early MS stars (e.g., A V) and red clump giants (RCGs), both with visual absolute magnitudes of $M_V = 0$. The former group is strictly composed of young stars and can be used to determine the global velocity field of young stars, while the K giants are a mixture of young, adolescent, and old stars. In the Galactic plane, these stars can be observed with parallax accuracies better than 10% out to distances of about 6 kpc. This distance limit is primarily set by the average extinction law of 1.5 mag kpc^{-1}. The large number density of RCGs (∼4000 stars kpc^{-2}) and A V stars (∼1700 kpc^{-2}) will allow for very detailed determination of the global rotation curve, as well as any "local" perturbations, where the "local" perturbations can be determined over a large fraction of the Milky Way disk.

3.2.3. The Radial Mass Distribution of the Milky Way

Of course, no one really knows the stellar mass distribution in galaxies, since we only measure the projected light distribution of the ensemble of stars. The integrated light is typically dominated by giant stars (or early-type MS stars in the spiral arms), which make up only a small fraction of the total stellar mass. Measured parallaxes, luminosities, and colors of stars yield approximate stellar masses and allow for the distinction to be made between main-sequence stars and giants. The Milky Way is the only galaxy for which such a detailed stellar census is possible. So, for the first time, the *OBSS* data will enable, via "simple" counting of stars, a direct determination of the radial distribution of stellar mass.

3.2.4. Spiral Structure of the Milky Way

OBSS will detect about the same number of G V stars with accurate parallaxes as *Gaia*. However, while *Gaia* data for G V stars will just reach to the first spiral arm (1–2 kpc), *OBSS* will measure the local total column density over large swaths of the spiral arm and interarm region (3–4 kpc). In addition, because the G V stars cover the whole range of stellar ages, it will be possible to assess whether the spiral arms are truly spiral density waves (stars of all ages participate in the wave, with an amplitude depending on the velocity dispersion), or whether spiral arms are just a wave of star formation (only the youngest stars participate in the wave). Since this test can be made over several arm segments, the differentiation between massive and massless spiral structure can be definitively made with *OBSS*.

3.2.5. Dark Matter Distribution

The vertical mass density distribution of the Milky Way is key to understanding the dark matter density distribution. Stellar motions that are vertical to the Galactic plane (in the z-direction) are sensitive to the total mass distribution [$M_{\rm tot}(z)$]. Subtracting the mass contributions of luminous matter (stars and gas; e.g., Bahcall 1984; Flynn & Fuchs 1994; Gould et al. 1997) yields the dark matter profile. The Milky Way is the only galaxy in which the local dark matter density distribution can be determined in situ. The current state of the art is that $M_{\rm tot}(z)$ is determined to $\pm 10\%$ out to about 1.1 kpc (Kuijken & Gilmore 1989, 1991). A better determination of $M_{\rm tot}(z)$ allows for a much better determination of the dark matter distribution and its shape (Olling & Merrifield 2000, 2001).

A very significant improvement of the *OBSS*-based analysis with respect to the ground-based analysis of Kuijken & Gilmore (1989, 1991) is that astrometric distances will be available, while in the late 1980s only photometric parallaxes were available, which were based on estimated vertical metallicity gradients. Due to its superior accuracy, the distance at which *OBSS* will provide 10% distance measurements is twice that of *Gaia* (to ∼12 kpc). This larger depth has two important consequences: (1) the distance in the plane (d_p) out to which $M_{\rm tot}(z)$ can be determined is about twice as large, while (2) the vertical height (z) is also about twice as large as that for *Gaia*, reaching to $z_{OBSS} = 5$ kpc toward the Galactic poles. The *OBSS* reach corresponds to an unprecedented 17 disk scale heights, and 5 scale heights of the thick disk. Even at a distance from the Sun of as large as $d_p = 4$ kpc, the *OBSS* vertical survey will reach to 3 kpc, or 10 vertical scale heights.

Apart from making a very accurate determination of $M_{\rm tot}(z)$, the *OBSS* data will also answer the very important question of how representative the currently known value of $M_{\rm tot}(z)$ is at the solar circle. That is to say, the *OBSS* data will allow for the determination of $M_{\rm tot}(z, R, \phi)$.

3.2.6. OB Associations

Most disk stars are formed in OB and T associations, rather than in gravitationally bound clusters. OB associations contain the most massive stars in the local part of the Galaxy and are therefore of paramount importance for the existence of biological life. The closest OB associations in the Scorpius-Centaurus region are only 110 to 160 pc away, stretching across the first Galactic quadrant of the sky. The most detailed study of the nearest OB associations to date was achieved with *Hipparcos*. It was found, perhaps not surprisingly, that the Sco-Cen associations included large numbers of F, G, and possibly lower mass stars from the *Hipparcos* astrometry (de Zeeuw et al. 1999). The mass function of OB associations is currently an ill-constrained issue of basic importance for NASA's Vision for Space Exploration, since most of the stars with life-bearing planets may have been formed in gravitationally unbound associations. It is possible that massive star clusters precede OB associations, and the first powerful supernova explosions in the cluster cores sweep out the remaining gas and trigger widespread formation of new stars in nearby associations. The embedded clusters are expected to be somewhat older than the ambient associations, but they should not necessarily have the same kinematics.

3.2.7. The Gould Belt

The Gould Belt is a disk-shaped structure that includes most of the stars younger than the Pleiades within ∼700 pc of the Sun, which is situated inside the belt. The Gould Belt is delineated on the sky by major concentrations of clouds of atomic and molecular gas and by the brightest O and B stars. Current studies of this surrounding structure are hampered by the lack of accurate astrometric and photometric information. The Gould Belt may contain more than 105 stars, and only a tiny fraction of the nearest and brightest stars have been listed. The survey character of *OBSS* and its high accuracy are ideal for these studies. The idea of triggered star formation due to high-velocity giant molecular cloud impacts could be tested, for example, by tracing the Galactic orbits of the components back in time and determining the place of origin and the distribution of ages.

3.2.8. Star Formation Regions and Giant Molecular Clouds

Sites of active star formation and giant molecular clouds with embedded Herbig-Haro objects and pre–main-sequence stars will be mapped within an unprecedented volume of space by *OBSS*. Unfortunately, the nearest regions of ongoing star formation were beyond the brightness and accuracy limits of *Hipparcos*. Thus, the dynamical aspects of star formation remain unknown. The distance to the Taurus-Auriga molecular cloud is ∼140 pc, and the stars are strongly reddened (Kenyon et al. 1994). *OBSS* will enable a detailed study of the shape, size, and density distribution of this cloud, which deserves a targeted field status. For a sizeable sample of nearby clouds (Hilton & Lahulla 1995), the much disputed but still uncertain differences of the extinction law will be verified.

3.2.9. Open Clusters and Stars Ejected from Them

OBSS will provide a scrutiny of open clusters in the near half of the Galaxy. Detailed isochrone ages, memberships, internal dynamics, and binarity status will be obtained for hundreds of known clusters, and undoubtedly, new ones will be discovered. One of the long-standing problems in Galactic dynamics is the survival of old open clusters. According to theoretical models and simulations, most open clusters are disrupted within several hundred Myr, and yet clusters older than 1 Gyr are known. Internal kinematics is a necessary piece of information to determine the dynamical mass of open clusters. Current estimates of cluster masses are quite uncertain (from 600 $M_\odot$ to several thousand $M_\odot$ for the Pleiades).

3.2.10. Galactic Halo, Tidal Streams, and Local Group

An *OBSS* survey of the Galactic halo would very much complement the *SIM PlanetQuest* Key Project: Taking Measure of the Milky Way (Majewski et al. 2002). If *OBSS* observes several years after *SIM PlanetQuest*, the proper motion accuracies from the combined missions will be superb.

The hierarchical buildup of galaxies is now the standard paradigm for the formation and evolution of galaxies in the presence of cold dark matter. A substantial fraction of the thousands of accumulated subhalos in a Milky Way–like galaxy are expected to persist to zero redshift (Kauffman 1999; Klypin et al. 1999; Moore et al. 1999), and a fraction of these are expected to have formed stars. Both simulations and analytical arguments (e.g., Tremaine 1993; Johnston et al. 1996) demonstrate that stars that are tidally torn from Galactic satellites remain concentrated in thin streamers trailing or leading the satellite along its orbit.

Because these tidal streams have an inherent dynamical "memory" to them, they offer new and powerful ways to probe not only the nature of the parent satellites (e.g., mass and dark matter content), but the shape, density law, lumpiness, and accretion history of the Milky Way halo as well (e.g., Johnston et al. 1999, 2005; Murali & Dubinski 1999; Font et al. 2001; Majewski et al. 2003; Law et al. 2005). The power of *OBSS* to make significant contributions in this area lies in the fact that halo streams are identifiable as clumps in phase-space associated with the orbital and internal energy properties of their parent satellites. By providing the two transverse motion dimensions in phase space, *OBSS* can be exploited for dramatic advances in the study of tidal streams in two general ways: (1) searches for new streams and (2) intense scrutiny of known streams.

OBSS can also provide critical and, usefully, precise proper motion results on large numbers of stars for inner halo streams, such as the Sagittarius, Monoceros, and Triangulum-Andromeda systems. As shown by Majewski et al. (2005), *OBSS*-precision proper motions of the Sagittarius tidal tails can yield a definitive measure of the long-sought speed of the local standard of rest, seen by reflex motion of the Sagittarius tails.

Proper motions for huge numbers of stars in the Monoceros "ring" system will be critical to the evaluation of warp versus tidal stream models and will establish quality orbits for this stellar population. The ability of *OBSS* to probe deeply and provide 20 μas proper motions for giant stars in outer halo streams will make possible new constraints on late infall and evolution of the Milky Way and its dark halo structure and provide direct tests of the cold dark matter paradigm. Proper motions combined with radial velocities of our Galactic neighbors tell us a great deal about the formation history of the Local Group, and hence about the very interesting period of the history of the universe during which a gravitational instability formed, collapsed, and formed individual galaxies. Such an in situ study of the dynamics of a small group of galaxies is very important for modelers of galaxy formation. Currently, it is difficult for the models to form groups such as the Milky Way–M31 pair and their dwarf companions.

3.2.11. Extragalactic Motion and Distances

Although the mean density of dark matter is now known with high accuracy, the dark matter distribution is not at all well determined. In the typical galaxy, total mass grows linearly with radius all the way until the end of the gas and star distributions; hence, we cannot directly measure where the growth ends. Gravitational lensing experiments give some statistical constraints on the outer distribution, but they cannot measure arbitrary mass distribution shapes and do not inform us much about any particular galaxy. Do the dark matter halos of the Andromeda galaxy and the Milky Way galaxy overlap to form a common envelope? Do groups of galaxies have dark matter components in addition to that ascribable to the individual galaxies? On the larger scales of clusters of galaxies, the X-ray gas indicates the amount of mass collocated with the galaxies, but it does not constrain the mass distribution at larger radii. It is known that neutrinos are abundant and have low masses, making them too hot for galaxies to capture, but what is the neutrino mean density, and is it possible that their distribution is enhanced around rich clusters? *OBSS* can probe for the answers to these hard questions about dark matter, which in turn reveal much about basic particle physics, such as neutrino and dark matter particle mass and related cosmology, including dissipational properties of dark matter, late-time galaxy merger rates, the virialization state of groups of galaxies, the small-scale density spectrum, the galaxy-mass bias function, the mass-to-light ratio as a function of mass and morphological type, and the impact of large-scale structure on the development of the small scales.

Using *OBSS*, it will be possible to measure proper motions of galaxies (the motion in the plane of the sky) out to the distance of the Virgo Cluster. These final two components of galaxy position momentum phase space are crucially important measurements of the deviation from purely radial Hubble flow and would be of lasting importance in the modeling of the formation of the Local Group galaxies (with $D < 2$ Mpc). *OBSS* would use the much more abundant stars in the tip of the red giant branch (TRGB) with absolute magnitudes between $M_V = -1.5$ and -2.5. There will be thousands of TRGB stars per galaxy, allowing for proper motion precisions down to 0.5 μas yr^{-1}. The expected velocities in the Local Group are of an order of 100 km s^{-1}, which translates to 11 μas yr^{-1} at 2 Mpc. If a sufficient number of quasi-stellar objects can be identified in the fields of the Local Group of galaxies, practically every nearby galaxy, no matter how small, will be accessible to *OBSS*.

On the analysis side, the measurements can be plugged into cosmological virial analysis, Zel'dovich linear analysis plus nonlinear extensions, and numerical analysis. Cosmological vi-

rial analysis will be greatly empowered by having three-dimensional velocity vectors rather than the one-dimensional radial velocity. On the large scales, Zel'dovich analysis can provide the initial distribution of matter from the present epoch phase-space information, which will then be compared to the microwave background measurements.

Much can be expected from the application of the numerical action method, which allows one to solve for the trajectories of the center of mass of galaxies, like an *N*-body simulation run backward in time. This technique can make use of the nine orbital parameters that will be known for each galaxy (right ascension, declination, redshift [radial velocity], distance, proper motion in right ascension and declination, and three components of peculiar velocity that at $t = 0$ are 0). When the cosmological parameters and the mass associated with each large galaxy are set correctly, a self-consistent model of the history of the gravitational interplay of galaxies is generated. Assuming a unique solution, one knows the true representation has been achieved when all of the present-day positions and velocities of the model agree with the observations within their errors, and the early-time peculiar velocities go smoothly to zero as time goes to zero. Out of this come accurate measurements of the local density, the fraction of matter not bound to any system, the age of the universe, global mass-to-light ratios, and individual mass-to-light ratios for the major galaxies, including all dark matter bound to that galaxy.

3.2.12. Reference Frames

The astrometric coordinates (positions, proper motions, and parallaxes) of objects observed with *OBSS* will be put on an absolute inertial reference frame, allowing astrophysical phenomena to be studied in unprecedented detail. For a fully dedicated survey mission, the accuracy of *OBSS* is comparable to the *Gaia* mission. Over 2 billion stars will be surveyed together with millions of extragalactic sources. The accuracy of the frame will be about a microarcsecond. In the proposed scenario in which the observing time for the survey is only 25% of the mission, the accuracy of the reference frame will be degraded by a factor of 2. If *Gaia* is successful, the *OBSS* observing program will be revised to use *Gaia* stars as fiducials in order to improve the positions of the extragalactic sources to accuracies of 20 μas at 21 mag.

The nature of black holes, which will anchor the reference frame (cores of quasars), will be investigated, as there will be millions of objects to study. Dark matter in the Milky Way will be discerned from its effect on the positions and motions of celestial sources by improving the positions of the *Gaia* stars in the 15–20 mag range. The bending of starlight passing close to the Sun and planets will allow an improved determination of the relativistic constants, as well as the shape of the Sun and planets. Direct detection of the motion of the solar system within the Milky Way, as well as the local group toward the Virgo Cluster, will also be discerned at the microarcsecond level. All of this will be accomplished by observing stellar motions with respect to distant "fixed" quasars, assuming the positional stability of quasars is as high as expected. The large number of quasars to be observed in the *OBSS* program ensures a high accuracy "average" absolute reference frame and at the same time enables possible detection of the apparent motion of the center of light of some "peculiar" quasar sources. The *OBSS* reference frame accuracy will supplant the current International Celestial Reference Frame (ICRF) by an order of magnitude, in addition to the frame established by the *Gaia* catalog. By establishing an accurate link between the optical *OBSS* frame and the radio ICRF, high-resolution imaging data at these disparate wavelengths can be accurately aligned to allow absolute, positional correlation. This enables excellent science return, including a better understanding of the mechanisms giving rise to an individual source's spectral energy distribution.

Absolute proper motions are required for the interpretation of galactic kinematics and investigations of galactic dynamics. Absolute trigonometric parallaxes out to many kpc and to high accuracy will allow construction of a three-dimensional picture of our Galaxy in the area where our solar system is located and will form the basis for accurate distance determinations on all scales.

3.3. New Science

3.3.1. Gravitational Physics

Microarcsecond space-based astrometry opens outstanding perspectives for experimental gravitational physics. A list of potentially measurable effects is presented below.

3.3.1.1. General Relativity

While general relativity remains the most probable candidate for the gravity theory, some alternative theories (including mathematical generalizations of general relativity) are being developed. In the limit of vanishing gravity, these theories give the same predictions as the customary theory of special relativity. However, in the presence of gravity their predictions differ. This necessitates more precise tests of relativity.

One such test is based on observation of light deflection in a static gravity field. The microarcsecond accuracy level of *OBSS* will not only enable a comparison of the measured deflection with the first-order post-Minkowskian calculations for the mass monopole, but will also provide an opportunity to observe the quadrupole first-order post-Minkowskian contribution due to the oblateness of the planets. The mass-monopole deflection has been measured many times, for the Sun and the planets. However, the sensitivity of *OBSS* will be sufficient to additionally measure this for planetary satellites to test general relativity predictions: 26 μas for the Moon, 30 μas for Io, 63 μas for Ganymede, 53 μas for Callisto, and 60 μas for Titan. The mass-quadrupole deflection emerges because a planet's oblateness makes the light deflection in the equatorial plane

different from that along the polar radius of the planet. For some planets, these differences are large enough to be measured by *OBSS*: 1056 μas for Jupiter, 576 μas for Saturn, 42 μas for Uranus, and 68 μas for Neptune (Klioner & Kopeikin 1992).

Another potentially available test of relativity can be carried out through measurements of the secular aberration caused by the circular motion of the solar system relative to the Galactic barycenter (Reid & Brunthaler 2004).

3.3.1.2. Propagation Speed of Gravity

Observation of light deflection by the giant planets of the solar system enables us to measure the speed of proliferation of gravity (Kopeikin 2001, 2004; Fomalont & Kopeikin 2003). While in the framework of Einstein's general relativity, the speed of gravity coincides with that of light, while in some alternative theories of gravity, there emerges a difference between these speeds. Therefore, experiments of this type provide new tests of relativity.

3.3.2. Solar System Objects

3.3.2.1. Trans-Neptunian Objects

The *OBSS* mission should produce a catalog of greatly improved orbital parameters and multicolor photometry of all small Sun-orbiting solar system objects brighter than 21 mag. The current database of such objects contains 230,000 asteroids and nine trans-Neptunian objects (TNOs). The TNOs are of course the largest ones known, generally larger than 600 km in diameter. Undoubtedly, more of these $m_v < 21$ TNOs will be found, but their numbers will be limited, and they are likely not to be typical of their parent class. Nevertheless, such a massive census of asteroids on a uniform astrometric and photometric system would provide a tool for further study that would be as valuable for dynamics and planetary physics as the *OBSS* star catalog would be for galactic astronomy.

The value of the photometry depends greatly on the bands chosen. Discrimination of asteroid surface composition depends on several broad spectral features at wavelengths between 0.3 and 1 μm. The main spectral features used in determining the taxonomy of an asteroid are the existence of a sharp decrease in reflectance shortward of 0.5 μm, the general slope of the reflectance between 0.5 and 1.1 μm, and the existence of a dip in reflectance around 1.0 μm. Unfortunately, wideband photometry (Tholen & Barucci 1989) does not give unique values for the different classes of asteroids. Instead, something like the proposed 16-band *OBSS* Low Resolution Spectrometer Instrument at approximately evenly spaced intervals from 0.3 to 1.1 μm is required to make a good determination of the different taxonomic types.

3.3.2.2. Small Bodies of the Solar System

Observation of small bodies and satellites will lead to a better understanding of the solar system and will also have important ramifications for the generic mechanisms of planetary system formation. The *OBSS* spacecraft will offer unparalleled opportunities in this area: detection of new objects, high-precision ephemeris measurement and orbital determination, observation of near-Earth objects (NEOs), determination of the rotational modes of objects, and a search for and study of binary asteroids. The ability of *OBSS* in this field will complement the *Gaia* mission. In full-time survey mode, its capabilities are similar. In the targeted field mode, its ability to conduct prolonged multiple observations of any patch of the sky at arbitrary time intervals will become crucial for high-precision ephemeris measurements.

OBSS will produce a catalog of greatly improved orbital parameters and photometry of all small Sun-orbiting solar system objects that are 21 mag and brighter if it is operated in the scan survey mode.

The *OBSS* spacecraft is ideally fit to search for new objects: near-Earth, main-belt, and trans-Neptunian objects of 21 mag and brighter. Typically, detection of a new object will require two observations of about a half-hour to an hour in one patch of sky (in the TNO case, it may be much longer). The *OBSS* target field mode is designed for observations of this type.

In the targeted field mode, many studies can be made using results of the 25% of time allocated for the *OBSS* survey or the data from the *Gaia* survey. For example, the *OBSS* mission will have a unique capability of determining the small bodies' orbits with a very high precision. After a new object is located, determination of its orbit requires an observation of this object a day later, then about 3 days later, and then about 9 days later, etc. (the total number of observations being dependent on the required precision). *OBSS* is capable of carrying out this sequence should these follow-up observations be of sufficient scientific merit.

The aforementioned ability of *OBSS* to aim for hours at the same patch of sky will make this spacecraft most effective in collecting photometric light curves, and also in the determination of the spin states and poles of small bodies. Typically, the light curves vary in depth over the spin period by 0.1–0.5 mag (Almeida et al. 2004). The mean rotation period of asteroids less than 10 km in diameter is about 6 hr, with most rotation periods lasting between 2 and 10 hr. For larger asteroids, the mean rotation period slowly increases to about 12 hr for an object 100 km in diameter (Pravec et al. 2002). This means that in principle, *OBSS* will be capable of measuring the spin states of the vast majority of asteroids brighter than 21st visual magnitude.

The ability of *OBSS* to aim at a designed part of the sky at required intervals will enable *OBSS* to determine masses of asteroids. Masses of asteroids can be determined from measurements of their mutual perturbations, but the smallness of the masses involved requires a close encounter between two objects in order to produce a measurable change in the orbital parameters. Basically, the mass of the larger body of the pair is determined by the change in orbital elements of the smaller

body caused by the encounter. Typical encounters last from 10 to 100 days and have minimum distances of 0.03–0.003 AU. Precise pre- and postencounter astrometric measurements are required. The typical encounter between asteroids results in a change in the mean motion of the perturbed asteroid on the order of 1–10 mas yr^{-1}. Thus, in order to make a mass determination good to 10%, the observations must be sufficiently precise to determine the uncertainty in the mean motion to about 0.1–1 mas yr^{-1}, both before and after the encounter.

OBSS will have an advantage in the search for binary asteroids. Detection of binary asteroids is important for two reasons. First, it is possible to determine the masses of the asteroid satellite system (in some cases, the motion of the asteroid and satellite around the center of mass has been detected, allowing a determination of the individual asteroid masses). Second, the relative sizes and orbital distances of the satellites vary with the general location of the asteroid in the solar system (near-Earth, main belt, or Kuiper Belt), hinting at differences in the formation or evolution of bodies in these regions. Thus, detection and observation of many more asteroid satellites would be extremely valuable. Most known asteroid satellite pairs do not have large differences in magnitude (although selection effects certainly are important); rather, the difficulty in detecting them is simply the relatively small separation between the components. In unresolved or marginally resolved images, it is difficult to decide between a satellite, an albedo feature, or an irregular shape. *OBSS*'s small point-spread function should allow many more of these pairs to be discovered.

4. FUTURE OUTLOOK

SIM PlanetQuest, *Gaia*, and *OBSS* are major missions costing an order of $1 billion dollars each. These missions take years of planning and significant resources. There is a limit on the resources available to space agencies. Both NASA and ESA are reviewing their future science missions in light of the projected funding for their agencies in the period 2007–2012. *Gaia* and *SIM PlanetQuest* have received substantial funding for development since 2000. *Gaia* is an astrophysics mission that is in implementation phase and is, as of this writing, on schedule for a 2011 launch. *SIM PlanetQuest* was scheduled for a 2011 launch in 2005, but given the budget outlook for science in 2007–2012, NASA is realigning the priority of its future missions. The *SIM PlanetQuest* launch may be delayed to 2016 or later. It would take 7 years to prepare *OBSS* for launch. If funded immediately, the earliest launch date would be 2014. Funding for *OBSS* would be from NASA, and therefore significant funding cannot likely be obtained before the launch of *SIM PlanetQuest*. Therefore, if *SIM PlanetQuest* survives and launches in 2016, this would put an *OBSS* launch in the time frame of 2023.

5. SUMMARY

There is a need for missions that exploit space capabilities of photometry and astrometry for astrophysics. The use of >1 m telescope apertures, together with wide FOVs with precise optics that are capable of astrometric measurements and large focal planes, make studies possible in all fields of solar system, Galactic, and extragalactic astrophysics. The mission that is under development, *Gaia*, will exploit this capability. However, this mission is not yet in space. The *OBSS* concept described here would not only achieve the science of the *Gaia* mission, but could also extend that science well beyond what is expected to be accomplished by *Gaia*. If *OBSS* were to fly after or during a successful *Gaia* mission, it would complement the bright and faint ends of *Gaia*'s sensitivity. The bright-star accuracy could be below 10 μas, while the astrometry between 16th and 20th visual magnitudes would also be improved by an order of magnitude. Objects could be studied in detail using any observing cadence dictated by the astrophysical goal. *OBSS* as a staring mission could reach objects fainter than 20th visual magnitude by using a longer integration time on interesting fields, such as dwarfs and tidal streams in the Milky Way. Light bending by planets such as Jupiter and the Earth could be studied in detail. Lensing by dark matter or energy could be viewed with the proper time sequence.

Given the present climate of high mission costs, an *OBSS* mission is a reasonable candidate for the time frame 2010–2020, since its costs can be reliably estimated to be under $800 million dollars. A wide-FOV, meter-class space telescope capable of precise astrometry and photometry using the stare mode can accomplish great science in addressing many areas of astrophysics, including but not limited to extrasolar planets, Galactic structure, the Galactic halo and tidal streams, the Local Group and local supercluster of galaxies, dark matter, star formation, open clusters, the solar system, and the celestial reference frame.

This research was supported by the National Aeronautics and Space Administration under a grant for Origins Science Mission Concept Studies NRA NNH04ZSS001N.

REFERENCES

Almeida, R., et al. 2004, A&A, 415, 403
Bahcall, J. N. 1984, ApJ, 276, 156
Bessell, M. S. 2005, Ann. Rev. A&A, 43, 293
Boss, A. P. 2006, ApJ, 643, 501
Dehnen, W. 1998, AJ, 115, 2384
———. 1999, ApJ, 524, L35
Deming, D., et al. 2005, Nature, 434, 740
de Zeeuw, P. T., et al. 1999, AJ, 117, 354
Du Mont, B. 1977, A&A, 61, 127
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Eisner, J. A., & Kulkarni, S. R. 2001, ApJ, 561, 1107
Famaey, B., et al. 2005, A&A, 430, 165

Flynn, C., & Fuchs, B. 1994, MNRAS, 270, 471
Fomalont, E. B., & Kopeikin, S. M. 2003, ApJ, 598, 704
Font, A. S., Navarro, J. F., Stadel, J., & Quinn, T. 2001, ApJ, 563, L1
Gould, A., et al. 1997, ApJ, 482, 913
Hilton, J., & Lahulla, J. F. 1995, A&AS, 113, 325
Johnston, K. V., et al. 1996, ApJ, 465, 278
———. 1999, AJ, 118, 1719
———. 2005, ApJ, 619, 800
Kaplan, G. H., & Makarov, V. V. 2003, Astron. Nachr., 324, 419
Kauffman, G. 1999, BAAS, 195, 6701
Kenyon, S. J., et al. 1994, AJ, 108, 1872
Klioner, S. A., & Kopeikin, S. M. 1992, AJ, 104, 897
Klypin, A., et al. 1999, ApJ, 522, 82
Kopeikin, S. M. 2001, ApJ, 556, L1
———. 2004, Classical Quantum Gravity, 21, 3251
Kuijken, K., & Gilmore, G. 1989, MNRAS, 239, 605
———. 1991, ApJ, 367, L9
Laughlin, G., Bodenheimer, P., & Adams, F. C. 2004, ApJ, 612, L73
Law, D. R., et al. 2005, ApJ, 619, 807
Liu, M. C., et al. 2002, ApJ, 571, 519
Mandushev, G., et al. 2005, ApJ, 621, 1061
Majewski, S. R., Muñoz, R. R., Westfall, K. B., & Patterson, R. J. 2005, in AIP Conf. Proc. 752, Stellar Astrophysics with the World's Largest Telescopes, ed. J. Mikolajewska & A. Olech (New York: AIP), 194
Majewski, S. R., et al. 2002, in *SIM PlanetQuest*: Science with the *Space Interferometry Mission*, ed. S. Unwin & S. Turyshev (JPL-2004-19; Pasadena: JPL), 15
———. 2003, ApJ, 599, 1082
Makarov, V. V., & Kaplan, G. H. 2005, AJ, 129, 2420
Moore, B., et al. 1999, MNRAS, 310, 1147
Murali, C., & Dubinski, J. 1999, AJ, 118, 911
Olling, R. P., & Dehenen, W. 2003, ApJ, 599, 275
Olling, R. P., & Merrifield, M. R. 2000, MNRAS, 311, 361
———. 2001, MNRAS, 326, 164
Orosz, J. A., et al. 2002, ApJ, 568, 845
Perryman, M., et al. 2001, A&A, 369, 339
Pravdo, S., Shaklan, S. B., & Lloyd, J. 2005, ApJ, 630, 528
Pravec, P., Harris, A. W., & Michalowski, T. 2002, Asteroids III, ed. W. F. Bottke, Jr., et al. (Tucson: Univ. Arizona Press), 113
Reid, M. J., & Brunthaler, A. 2004, ApJ, 616, 872
Soederhjelm, S. 1999, A&A, 341, 121
Tabachnik, S., & Tremaine, S. 2002, MNRAS, 335, 151
Tholen, D. J., & Barucci, M. A. 1989, in Asteroids II (A90-27001 10-91; Tucson: Univ. Arizona Press), 298
Tremaine, S. 1993, in AIP Conf. Proc. 278, Back to the Galaxy, ed. S. S. Hold & F. Verter (New York: AIP), 599
Turon, C., O'Flaherty, K. S., & Perryman, M. A. C., ed. 2005, The Three-Dimensional Universe with *Gaia* (ESA SP-576; Noordwijk: ESA)
Vityazev, V., & Shuksto, A. 2004, in ASP Conf. Ser. 316, Order and Chaos in Stellar and Planetary Systems, ed. G. Byrd et al. (San Francisco: ASP), 230
Zacharias, N. 1992, A&A, 264, 296
Zacharias, N., & Dorland, B., 2006, PASP, 118, 1419